

AD-A200 301

LASER WAKEFIELD ACCELERATION AND RELATIVISTIC OPTICAL  
GUIDING(U) NAVAL RESEARCH LAB WASHINGTON DC  
P SPRANGLE ET AL. 12 SEP 88 NRL-MR-6267

1/1

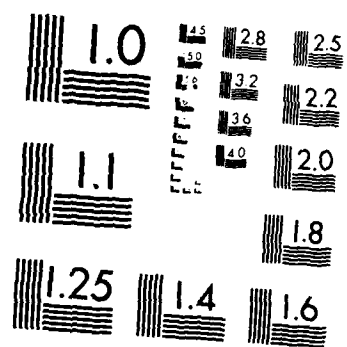
UNCLASSIFIED

F/G 20/7

NL



UNC



Naval Research Laboratory

Washington, DC 20375-5000



NRL Memorandum Report 6267

AD-A200 381

## Laser Wakefield Acceleration and Relativistic Optical Guiding

P. SPRANGLE

*Plasma Theory Branch  
Plasma Physics Division*

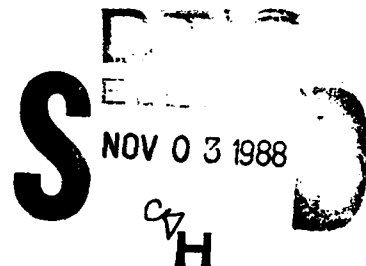
E. ESAREY AND A. TING

*Berkeley Research Associates, Inc.  
Springfield, VA 22150*

G. JOYCE

*Plasma Theory Branch  
Plasma Physics Division*

September 12, 1988



SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE			Form Approved GSA GEN. REG. NO. 27	
1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			2b. DECLASSIFICATION/DOWNGRADING SCHEDULE Approved for public release; distribution unlimited.	
2a. SECURITY CLASSIFICATION AUTHORITY			3. MONITORING AND EVALUATION STATEMENTS	
4. PERFORMING ORGANIZATION REPORT NUMBER NRL Memorandum Report 6267			5. MONITORING AND EVALUATION STATEMENTS	
6a. NAME OF PERFORMING ORGANIZATION Naval Research Laboratory	6b. OFFICE SYMBOL (If applicable) Code 4790	7a. NAME OF MONITORING AND EVALUATION ORGANIZATION		
6c. ADDRESS (City, State, and ZIP Code) Washington, DC 20375-5000		7b. ADDRESS (City, State, and ZIP Code)		
8a. NAME OF FUNDING SPONSORING ORGANIZATION U.S. Department of Energy	8b. OFFICE SYMBOL (If applicable)	9. MONITORING AND EVALUATION STATEMENTS		
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20545		10. MONITORING AND EVALUATION STATEMENTS		
		DOE	NO A105-83 ER40117 Mod A004	
11. TITLE (Include Security Classification) Laser Wakefield Acceleration and Relativistic Optical Guiding				
12. PERSONAL AUTHOR(S) Sprangle, P., Esarey, * E., Ting, * A. and Joyce, G.				
13a. TYPE OF REPORT	13b. TIME COVERED FROM TO	14. DATE OF REPORT (Year, Month, Day) 1988 September 12		15. NUMBER OF PAGES 28
16. SUPPLEMENTARY NOTES *Berkeley Research Assoc., Inc., Springfield, VA 22150				
17. COSAT CODES		18. SUBJECT TERMS (Continue on reverse if necessary; indentify by block number)		
FIELD	GROUP	SUBGROUP		
		Laser Accelerator		
		Wakefield		
19. ABSTRACT (Continue on reverse if necessary and identify by block number) An electron acceleration method is investigated which employs a short ( $\tau_L \sim 2\pi\omega_p^{-1} \approx 1$ picosec), high power ( $P \geq 10^{15}$ W), single frequency laser pulse to generate large amplitude ( $E \geq 1$ GeV/m) plasma waves (wakefields). At sufficiently high laser powers ( $P \geq 17 (\omega/\omega_p)^2$ GW), relativistic optical guiding may be used to prevent the pulse from diffracting within the plasma.				
20. DISTRIBUTION STATEMENT (For example: UNCLASSIFIED)		21. DISTRIBUTION STATEMENT (For example: UNCLASSIFIED)		
22. AUTHOR (Last Name, First Name, Middle Initial) P. Sprangle		23. AUTHOR (Last Name, First Name, Middle Initial) (202) 267-8393 Code 4790		

## CONTENTS

INTRODUCTION .....	1
OPTICAL GUIDING .....	3
ACCELERATION MECHANISM .....	5
NUMERICAL RESULTS .....	8
DISCUSSION .....	8
ACKNOWLEDGEMENTS .....	10
REFERENCES .....	11
DISTRIBUTION LIST .....	17



Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Avail and/or	
Dist	Special
A-1	

# LASER WAKEFIELD ACCELERATION AND RELATIVISTIC OPTICAL GUIDING

## Introduction

It has been suggested that the next generation of high energy linear electron accelerators utilize the extremely high gradients associated with plasma waves. Excitation of plasma waves having gradients as high as several tens of GeV/m can be accomplished in a number of related ways. The plasma based acceleration schemes which have received the most attention are the plasma beat wave accelerator<sup>1</sup> (PBWA) and the plasma wakefield accelerator<sup>2</sup> (PWFA).

The purpose of this report is to propose a laser plasma electron acceleration scheme<sup>3</sup> which utilizes a relativistic optical guiding mechanism. Relativistic optical guiding<sup>4,5</sup> may allow a sufficiently high power laser pulse to propagate long distances within a plasma. The principle of this optically guided laser wakefield accelerator (LWFA) is that a short ( $\tau_L \sim 2\pi/\omega_p \sim 1$  picosec), high power ( $P \gtrsim 10^{15}$  W), single frequency laser pulse could propagate long distances in a plasma and produce accelerating wakefields in a manner analogous to that in the PWFA (see Fig. 1). In the LWFA, however, the plasma responds to the ponderomotive forces of the laser pulse as opposed to the self-fields of the electron beam as in the PWFA. In addition, in the LWFA the plasma wave is not resonantly excited as it is in the PBWA. Therefore, the plasma density in the LWFA concept does not have to be finely adjusted to achieve large amplitude accelerating fields. The idea of generating a plasma wave using a single frequency, short pulse laser was suggested by Tajima and Dawson,<sup>1</sup> but apparently was not pursued. More detailed consideration of the laser propagation issues, along with recent advances in laser technology, indicate that the single frequency, short pulse LWFA together with relativistic optical guiding may have advantages over the PBWA and PWFA schemes.

In the PBWA the plasma wave is excited by the beating of two relatively low power, long pulse laser beams having a frequency difference equal to the plasma frequency. The beat (ponderomotive) wave resonantly drives the plasma wave to large amplitudes. In the PWFA concept, a low energy, high current relativistic electron beam (driver) having an appropriate current profile travels through a plasma leaving behind a large amplitude plasma wave (wakefield). The wakefield accelerates a second low current, high energy relativistic electron beam. A necessary criteria for successful operation of either the PBWA or the PWFA is that the driver, i.e., radiation or electron beam, must be capable of propagating a sufficiently long distance within the plasma.

Both the PBWA and the PWFA concepts have a number of unresolved issues. In the PBWA, these include fine tuning of the laser frequencies and plasma density to within a fraction of a percent to allow for resonant growth of the plasma wave.<sup>6</sup> Also the laser beams must propagate large distances within the plasma, avoiding i) diffraction, ii) laser-plasma instabilities, iii) phase detuning between the plasma waves and the accelerated electrons, as well as iv) energy depletion of the driving laser beams.<sup>7</sup> The problems regarding the PWFA involve the technology of producing a high current driving beam with a slow rise time and a very rapid fall time,<sup>8</sup> of the order of picoseconds, as well as the stable propagation of such a beam over large distances within the plasma. Multiple acceleration stages, all sequentially phase synchronized, have been proposed to overcome the propagation distance limitation in both the PBWA and PWFA. Multi-staging appears to be extremely difficult from a practical point of view.



### Optical Guiding

The need for optical guiding in the LWFA becomes apparent when the various limitations placed on the acceleration distance are considered. One limitation on the acceleration distance is the diffraction length,  $L_d$ , which characterizes the distance over which the laser beam spreads transversely. In the absence of some form of optical guiding, the diffraction length is given by the vacuum Rayleigh length,  $L_d = \pi r_L^2 / \lambda$ , where  $r_L$  is the laser spot size and  $\lambda$  is the wavelength. Another limitation on the acceleration length is the phase detuning distance,<sup>1,7</sup>  $L_t \equiv 2 \gamma_L^2 \lambda_p \approx 2(1 + \lambda_p^2 / 4r_L^2)^{-1} (\lambda_p / \lambda)^2 \lambda_p$ , where  $\gamma_L^{-2} = (1 - v_g^2 / c^2)$ ,  $v_g$  is the group velocity of the laser pulse and  $\lambda_p$  is the plasma wavelength. The phase detuning length is the distance over which an ultra relativistic electron outruns the wakefield of the radiation pulse and no longer gains energy. In addition to  $L_d$  and  $L_t$  there is also the laser depletion length,<sup>9</sup>  $L_p \equiv E_L^2 \ell_L / E_z^2 \approx \ell_L (\ell_L / \lambda)^2 / a_{Lo}^2$ , where  $E_L$  is the laser electric field,  $\ell_L$  is the laser pulse length,  $E_z$  is the axial wake electric field and  $a_{Lo}$  is the normalized vector potential amplitude of the radiation field,  $a_{Lo} = |e| A_{Lo} / (m_o c^2)$ . When the pulse travels a distance  $L_p$ , the energy in the trailing plasma wakefield becomes comparable to the laser pulse energy. Typical values for  $L_d$ ,  $L_t$  and  $L_p$  are  $\sim 1$  m,  $\sim 100$  m and  $\sim 1000$  m respectively. In obtaining these estimates the following parameters were used:  $\lambda \sim 1 \mu\text{m}$ ,  $a_{Lo} \sim 0.5$  and  $\ell_L \sim r_L \sim \lambda_p \sim 0.5$  mm. The primary limitation on the acceleration distance is due to diffraction,  $L_d$ . Clearly, some form of optical guiding within the plasma is necessary to avoid the need for multi-stage acceleration.

The optical guiding mechanism which may be appropriate for the intense, short laser pulse in the LWFA is that of relativistic guiding.<sup>4,5</sup> Physically, relativistic guiding results from the quiver motion of the

plasma electrons in the radiation field,  $v_q = ca_L/\gamma_L$ , where  $\gamma_L(r) = (1+a_L^2(r))^{1/2}$ . This gives an index of refraction  $n(r) = (1-(\omega_{po}^2/\omega^2)/\gamma_L(r))^{1/2}$ , where  $\omega_{po}$  is the ambient electron plasma frequency and  $\omega$  is the laser frequency. If the radiation beam is peaked on axis, then  $\partial n/\partial r < 0$ , which is a necessary requirement for refractive guiding to occur. Relativistic optical guiding occurs on a fast time scale of order  $\omega^{-1}$ ; hence, it can affect short pulse radiation,  $\omega^{-1} \ll \ell_L/c \lesssim \omega_p^{-1}$ .

Using the ray equations from geometric optics, it is possible to derive an envelope equation<sup>5</sup> for the evolution of the normalized spot size  $x \equiv r_L/(a_{Lo}r_{Lo})$  of the radiation beam, where  $r_{Lo}$  is the initial spot size. The envelope equation is of the form of a particle moving in an effective potential,  $d^2x/dt^2 = -V_0 \partial V/\partial x$ . The effective potential  $V(x)$  is given by  $\partial V/\partial x = -x^{-3} + 16\alpha x[g(x) - 2 \ln(g(x)/2+1)]$ , where  $V_0 = (2c^2/(\omega r_{Lo}^2 a_{Lo}^2))^2$ ,  $\alpha = (\omega_{po} a_{Lo} r_{Lo}/(4c))^2$ , and  $g(x) = (1+x^{-2})^{1/2}-1$ . Analysis<sup>5</sup> indicates that the effective potential contains a minimum provided  $\alpha > 1$ , thus allowing for matched beam (constant spot size) solutions. Physically,  $\alpha$  can be written, in terms of the laser power  $P$ , as  $\alpha = P/P_{cr}$ , where  $P_{cr} \approx 17(\omega/\omega_p)^2$  GW is the critical power threshold for relativistic optical guiding. The high power levels needed for relativistic optical guiding in plasmas are consistent with the intense laser pulses needed in the LWFA.

Two points should be mentioned with regard to the propagation of finite length pulses of duration  $\ell_L/c \lesssim \omega_p^{-1}$ . The first is that relativistic optical guiding may also lead to "pulse clipping". That is, the front and back regions of the pulse where  $P < P_{cr}$  will not be guided but instead will diffract away, leaving a shortened pulse. Only the central region of the pulse, where  $P > P_{cr}$ , will propagate. The second point concerns longitudinal dispersive spreading. It can be shown that

after propagating a detuning length  $L_t$ , the intrinsic frequency spread of the beam  $\Delta\omega$  causes the pulse to spread by the amount  $\Delta\ell_L \approx 2(\Delta\omega/\omega)\lambda_p$ . Since  $|\Delta\omega/\omega| \ll 1$ , longitudinal dispersive spreading should not be a problem.

### Acceleration Mechanism

In the relativistically guided LWFA concept the short pulse, high power laser beam provides both a radial and axial ponderomotive force on the plasma electrons. The radial ponderomotive force expels electrons radially outward while the front (back) of the laser pulse exerts a forward (backward) force on the electrons. In this sense, the laser pulse acts approximately like a negatively charged macro particle propagating through the plasma (see Fig. 1). As the plasma electrons flow around the laser pulse, large amplitude plasma waves are generated.

The ponderomotive force, exerted by the laser pulse on the plasma, moves at the pulse's group velocity and is given by  $F_{\text{pond}} = |e|\nabla\Phi_L(r,z,t)$ , where the ponderomotive potential is  $\Phi_L \approx -m_0 c^2 a_L^2 / (2|e|)$ . Note that the axial ponderomotive force from the laser pulse cannot be used directly to accelerate electrons to high energies. The ponderomotive force on the accelerated electrons is smaller than that on the plasma electrons by the factor  $1/\gamma$ , where  $\gamma$  is the relativistic factor associated with the accelerated electrons. The laser pulse must first excite a plasma wave which, in turn, can be used for acceleration. In this analysis the laser beam is assumed to be circularly polarized, although a linearly polarized laser, apart from generating harmonics, would have been equally satisfactory.

The wave equation for the plasma response or wakefield is

$$\nabla^2 \tilde{E} - \frac{1}{c^2} \frac{\partial^2 \tilde{E}}{\partial t^2} = \frac{4\pi}{c^2} \frac{\partial \tilde{J}_p}{\partial t} - 4\pi |e| \nabla \delta n_p, \quad (1)$$

where  $\tilde{J}_p$  and  $\delta n_p$  are the plasma response electron current and number density respectively. It proves convenient to perform an algebraic transformation to the speed of light frame ( $\zeta = z - ct$ ,  $\tau = t$ ). The transformation should actually be to the laser pulse group velocity frame, but the differences can be neglected for the present purposes. Furthermore, a temporal steady state,  $\partial/\partial\tau = 0$ , in the laser pulse frame is assumed. It can be shown that for short laser pulses with  $a_{Lo}^2/2 \ll 1$ , the plasma quantities remain linear and nonrelativistic. The plasma, therefore, is assumed to be described by the linear, nonrelativistic, cold fluid equations. Using this fluid response,  $\tilde{J}_p$  and  $\delta n_p$ , in the wave equation, the plasma response fields and density are given by

$$\left( \frac{\partial^2}{\partial \zeta^2} + k_p^2 \right) \tilde{E}(r, \zeta) = k_p^2 \tilde{\nabla} \phi_L(r, \zeta), \quad (2)$$

$$\left( \frac{\partial^2}{\partial \zeta^2} + k_p^2 \right) \delta n_p(r, \zeta) = - \frac{|e| n_{po}}{m_o c^2} \nabla^2 \phi_L(r, \zeta), \quad (3)$$

where  $k_p = \omega_{po}/c$  and  $\tilde{\nabla} = \hat{e}_r \partial/\partial r + \hat{e}_z \partial/\partial \zeta$ . Note that even in the two-dimensional case the response field,  $\tilde{E}$ , is derivable from a scalar potential and hence, there is no response magnetic field.

From (2), the axial wakefield is given by

$$E_z(r, \zeta) = - k_p^2 \int_{\zeta}^{\infty} \cos k_p(\zeta - \zeta') \phi_L(r, \zeta') d\zeta'. \quad (4)$$

From (2) and (3) it can be shown that the transverse wakefield and plasma density are given by  $\partial E_r/\partial \zeta = \partial E_z/\partial r$  and  $\partial \delta n_p/\partial \zeta = -(4\pi |e|)^{-1} \nabla^2 E_z$ .

As an illustration, consider a laser pulse profile of the form  $a_L(r, \zeta) = a_{Lo} \sin(\pi \zeta / \ell_L) \exp(-r^2 / r_L^2)$  for  $0 \leq \zeta \leq \ell_L$  and 0 otherwise. Then the axial wakefield and response plasma density within the laser pulse,  $0 \leq \zeta \leq \ell_L$ , and behind the pulse,  $\zeta \leq 0$ , are given by

$$E_z(\zeta, r) = - \frac{2\pi^2 k_p \phi_{Lo}(r)}{4\pi^2 - k_p^2 \ell_L^2} \left[ \sin k_p \ell_L (1 - \tilde{\zeta}) + h \sin(k_p \ell_L \tilde{\zeta} / h) \right], \quad (5)$$

and

$$\begin{aligned} \frac{\delta n_p(z)}{n_{po}} = & - \frac{2|e|}{m_o c^2} \frac{\pi^2 \phi_{Lo}(r)}{(4\pi^2 - k_p^2 \ell_L^2)} \left\{ \cos k_p \ell_L (1 - \tilde{\zeta}) - \cos(k_p \ell_L \tilde{\zeta} / h) \right. \\ & \left. + \frac{8}{k_p^2 r_L^2} \left( 1 - \frac{2r^2}{r_L^2} \right) \left[ \cos k_p \ell_L (1 - \tilde{\zeta}) - 1 - h^2 (\cos(k_p \ell_L \tilde{\zeta} / h) - 1) \right] \right\}, \quad (6) \end{aligned}$$

where  $\tilde{\zeta} = \zeta / \ell_L$ ,  $k_p = 2\pi / \lambda_p$ ,  $\phi_{Lo}(r) = -(m_o c^2 / 2 |e|) a_{Lo}^2 \exp(-2r^2 / r_L^2)$  and

where  $h = k_p \ell_L / 2\pi$  for  $0 \leq \tilde{\zeta} \leq 1$  and  $h = 1$  for  $\tilde{\zeta} \leq 0$ . The transverse wakefield is easily calculated from (5) by the relation  $\partial E_L / \partial \zeta = \partial E_z / \partial r$ . It can be shown, as is true of PWFA, that there exists a region of length  $\lambda_p / 4$  in the laser pulse frame over which the accelerated electrons experience both an accelerating axial field as well as a focusing radial field.

The axial wakefield in (5) is maximum when the laser pulse length is nearly equal to the plasma wavelength,  $\ell_L \approx \lambda_p$ . For  $\ell_L = \lambda_p$ , the maximum accelerating field is approximately  $\pi$  times larger than the maximum ponderomotive axial field  $E_{z, \max} \approx \pi E_{\text{pond}, \max} = \pi^2 \phi_{Lo} / \ell_L$ . It can be shown that the maximum accelerating field is fairly insensitive to changes in the laser pulse length and/or the ambient plasma density. It should be noted that (5) and (6) also indicate that it is possible to operate the LWFA in a

"wakeless" regime (i.e., the plasma response is nonzero only within the region of the laser pulse) when  $\ell_L = m\lambda_p$ , where  $m$  is an integer  $\geq 2$ .

### Numerical Results

The results for the plasma response given by (5) and (6) are plotted in Fig. 2 for the parameters  $\ell_L = \lambda_p = 0.03$  cm,  $a_{Lo}^2 = 0.31$  and  $r_L = 0.038$  cm. The values of  $a_{Lo}$  and  $r_L$  are those required<sup>5</sup> for a relativistic optical guided beam when  $\alpha = P/P_{cr} = 1.2$ . The axial wakefield is shown by the solid curve and the density wake is shown by the dashed curve. The maximum accelerating gradient for this example is 2.6 GeV/m. Recall that the laser pulse extends over the region  $0 \leq \xi \leq 1$ .

In order to further examine the principles of the LWFA, a full scale simulation was performed using the electromagnetic particle code<sup>10</sup> FRIEZR. FRIEZR is a 2 1/2D, fully relativistic, electromagnetic PIC code for electrons with a fluid ion background. The simulation is carried out in the transformed laboratory frame of  $\zeta = z - ct$ . The laser field was modeled by a fixed external ponderomotive force moving at the speed of light. The resulting axial wakefield is shown in Fig. 3 for the same parameters as used in Fig. 2. The results shown in Fig. 3 are in good agreement with analytic theory.

### Discussion

The above analysis indicates that the LWFA is capable of generating acceleration gradients on the order of a few GeV/m by propagating a single, short pulse, high power laser beam through a plasma. Equation (5) gives a maximum acceleration gradient of  $E_{max} \approx m_0(c\pi a_{Lo})^2/(2|e|\ell_L)$ . In addition, relativistic optical guiding occurs for sufficiently high radiation powers,  $P \geq P_{cr}$ . If the radiation pulse is optically guided, the acceleration

distance will be limited to the phase detuning length,  $L_t$ , instead of the much shorter free space Rayleigh length,  $L_d$ . This indicates a maximum single stage energy gain of  $\mathcal{E} \equiv L_t E_{\text{max}} \approx 2\alpha\lambda_p^4/(\lambda r_L)^2$ , where  $\alpha = P/P_{\text{cr}}$ . Table 1 summarizes these results for a  $\text{CO}_2$ , an Nd glass and a KrF laser, each of 1 psec pulse duration. In each case  $\alpha = 1.2$  which implies  $a_{\text{Lo}}^2 = 0.31$  and  $r_L = 0.038$  cm for a matched beam propagation in the relativistic optically guided<sup>5</sup> propagation mode.

The present analysis of relativistic optical guiding neglects the effects of the electron density response on the laser pulse. Such an approximation is appropriate when  $\delta n_p/n_{p0} \ll a_{\text{Lo}}^2/2$ . For the present analysis, however, this condition is only marginally satisfied for parameters of interest. In addition, laser-plasma instabilities<sup>11,12</sup> such as the filamentation, self-modulation or Raman scattering processes have not been considered for relativistically guided short pulses. It is anticipated that by keeping the dimensions of the laser pulse small,  $r_L \sim r_L \leq \lambda_p$ , the effects of these instabilities may be minimized. For example, Raman scattering processes<sup>12</sup> occur through the development of plasma waves within the laser pulse. Since the length scale for the development of plasma waves is  $\lambda_p$ , such effects may be suppressed if  $r_L \leq \lambda_p$ . In addition, relativistic filamentation<sup>11</sup> is a result of unstable transverse modes with  $k_{\perp}^{-1} > \lambda_p$ . Again, this instability may be suppressed in laser pulses with  $r_L \sim \lambda_p$ . Furthermore, random fluctuations in the plasma density will result in spreading of the laser spot size. A more self-consistent model of relativistic optical guiding for finite pulse lengths is currently being pursued by the authors.

The LWFA may have advantages over both the PWFA and the PBWA. For example, in the PWFA, it is necessary to use a high current (tens of kA) driving electron beam with a long rise time ( $\gg \omega_p^{-1}$ ) and a rapid fall time

$(\ll \omega_p^{-1})$ .<sup>8</sup> Stable propagation within a plasma of a high current electron beam which has a pulse length greater than  $\omega_p^{-1}$  may be difficult. Similarly, in the PBWA, resonant amplification of the plasma wave requires that the laser beams have long pulse lengths (many plasma periods in extent). It is likely that propagation of these long pulse beams will be plagued by the usual laser-plasma instabilities. In addition, such resonant amplification requires fine tuning between the frequency differences of the two lasers and the plasma frequency.<sup>6</sup> This fine tuning, which is not necessary in the LWFA, may be difficult to achieve in practice. Although the maximum gradients attainable in the LWFA may be lower than in the PBWA, the many apparent advantages (i.e., relativistic optical guiding, stability and simplicity) of using a single, intense, short pulse laser beam, makes the LWFA an attractive acceleration scheme.

#### Acknowledgments

The authors would like to acknowledge useful discussions with C. M. Tang and J. Krall. This work was supported by U. S. Department of Energy.



### References

1. T. Tajima and J. M. Dawson, Phys. Rev. Lett. 43, 267 (1979).
2. P. Chen, J. M. Dawson, R. W. Huff and T. Katsouleas, Phys. Rev. Lett. 54, 693 (1985).
3. P. Sprangle, E. Esarey, A. Ting and G. Joyce, presented at the Nonneutral Plasma Physics Symposium, National Academy of Sciences, Washington, DC, March 28-29, 1988; also presented at the Spring Meeting of the American Physical Society, Baltimore, MD, April 18-21, 1988.
4. C. Max, J. Arons and A. B. Langdon, Phys. Rev. Lett. 33, 209 (1974); G. Schmidt and W. Horton, Comments Plasma Phys. 9, 85 (1985); G. Z. Sun, E. Ott, Y. C. Lee and P. Guzdar, Phys. Fluids 30, 526 (1987).
5. P. Sprangle and C. M. Tang, in Laser Acceleration of Particles, ed. by C. Joshi and T. Katsouleas, AIP Conf. Proc. No. 130 (Amer. Inst. Phys., New York, 1985), p. 156; P. Sprangle, C. M. Tang and E. Esarey, IEEE Trans. Plasma Sci. PS-15, 145 (1987).
6. C. M. Tang, P. Sprangle and R. N. Sudan, Appl. Phys. Lett. 45, 375 (1984); Phys. Fluids 28, 1974 (1985).
7. T. Katsouleas, C. Joshi, J. M. Dawson, F. F. Chen, C. E. Clayton, W. B. Mori, C. Darrow and D. Umstadter, in Laser Acceleration of Particles, ed. by C. Joshi and T. Katsouleas, AIP Conf. Proc. No. 130 (Amer. Inst. Phys., New York, 1985), p. 63.
8. P. Chen and J. M. Dawson, in Laser Acceleration, ed. by C. Joshi and T. Katsouleas, AIP Conf. Proc. No. 130 (Amer. Inst. Phys., New York, 1985), p. 201.
9. W. Horton and T. Tajima, in Laser Acceleration of Particles, ed. by C. Joshi and T. Katsouleas, AIP Conf. Proc. No. 130 (Amer. Inst. Phys., New York, 1985), p. 179; Phys. Rev. A 34, 4110 (1986).

10. G. Joyce, Bull. Amer. Phys. Soc. 32, 1766 (1987).
11. C. Max, J. Arons and A. B. Langdon, Phys. Rev. Lett. 33, 209 (1974).
12. D. W. Forslund, J. M. Kindel and E. L. Lindman, Phys. Fluids 18, 1002 (1975).

Table 1 The laser power ( $P$ ), diffraction length (free space Rayleigh length,  $l_d$ ), detuning length ( $L_t$ ) and single stage energy gain ( $\mathcal{E} = E_z L_t$ ) for three lasers:  $\text{CO}_2$ , Nd glass and KrF. The parameters are chosen to correspond to a relativistic optically guided beam with  $P/P_{\text{cr}} = 1.2$ ,  $a_{\text{Lo}}^2 = 0.31$  and  $r_L = 0.038$  cm. This gives an acceleration gradient of  $E_z = 2.6$  GeV/m for  $\ell_L = \lambda_p = 0.03$  cm.

Laser	$\lambda[\mu\text{m}]$	$P[\text{W}]$	$L_d[\text{m}]$	$L_t[\text{m}]$	$\mathcal{E}[\text{GeV}]$
$\text{CO}_2$	10.6	$1.9 \times 10^{13}$	0.045	0.54	1.4
Nd-glass	1.06	$1.9 \times 10^{15}$	0.45	54	140
KrF	0.26	$3.0 \times 10^{16}$	1.8	860	2200

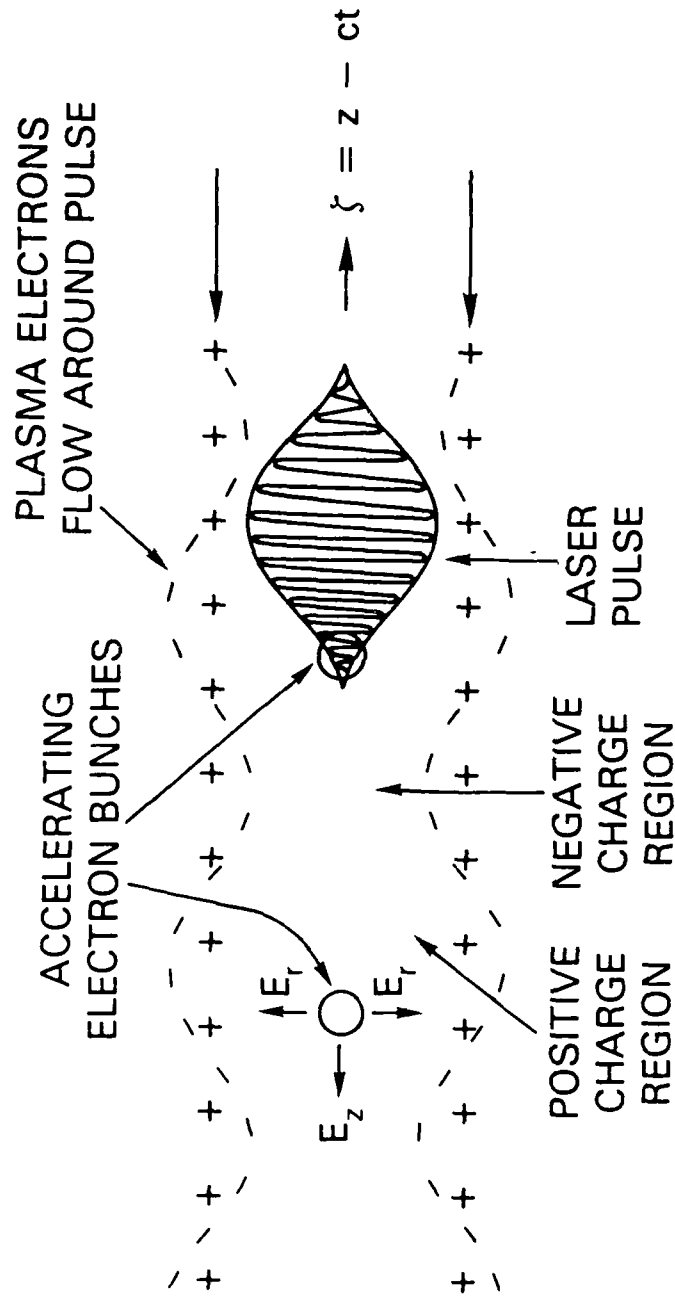


Fig. 1 Schematic of the LWFA showing the ponderomotive force from an intense short pulse laser generating a plasma wave wake as it propagates through the plasma. Roughly speaking, the laser pulse acts like an intense negative charge by repelling electrons in both the radial and axial directions.

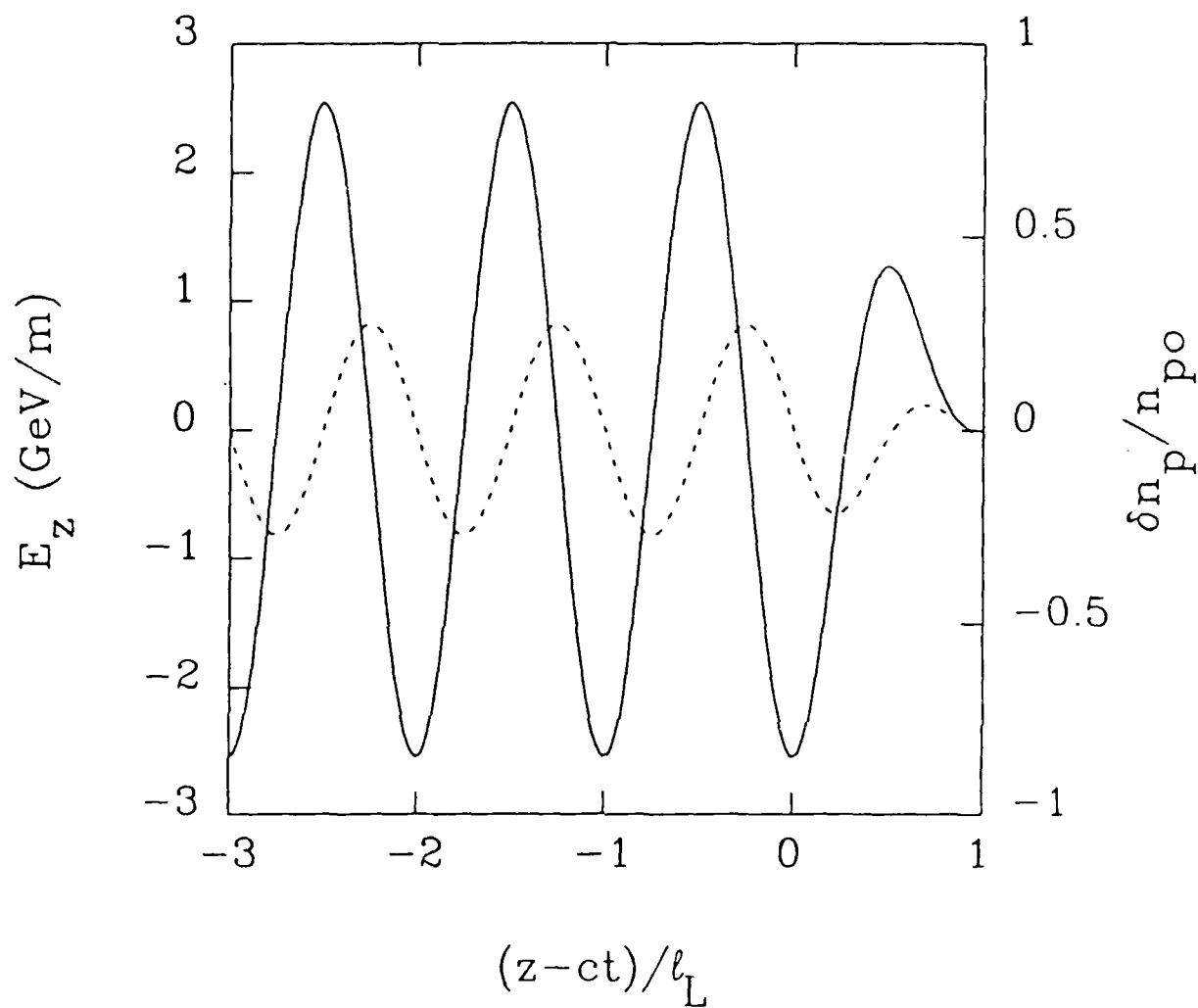


Fig. 2 The axial wakefield (solid curve) and density wake (dashed curve) for for  $\ell_L = \lambda_p = 0.03$  cm,  $a_{Lo}^2 = 0.31$  and  $r_L = 0.038$  cm. The laser pulse extends over the region  $0 \leq (z-ct)/\ell_L \leq 1$ .

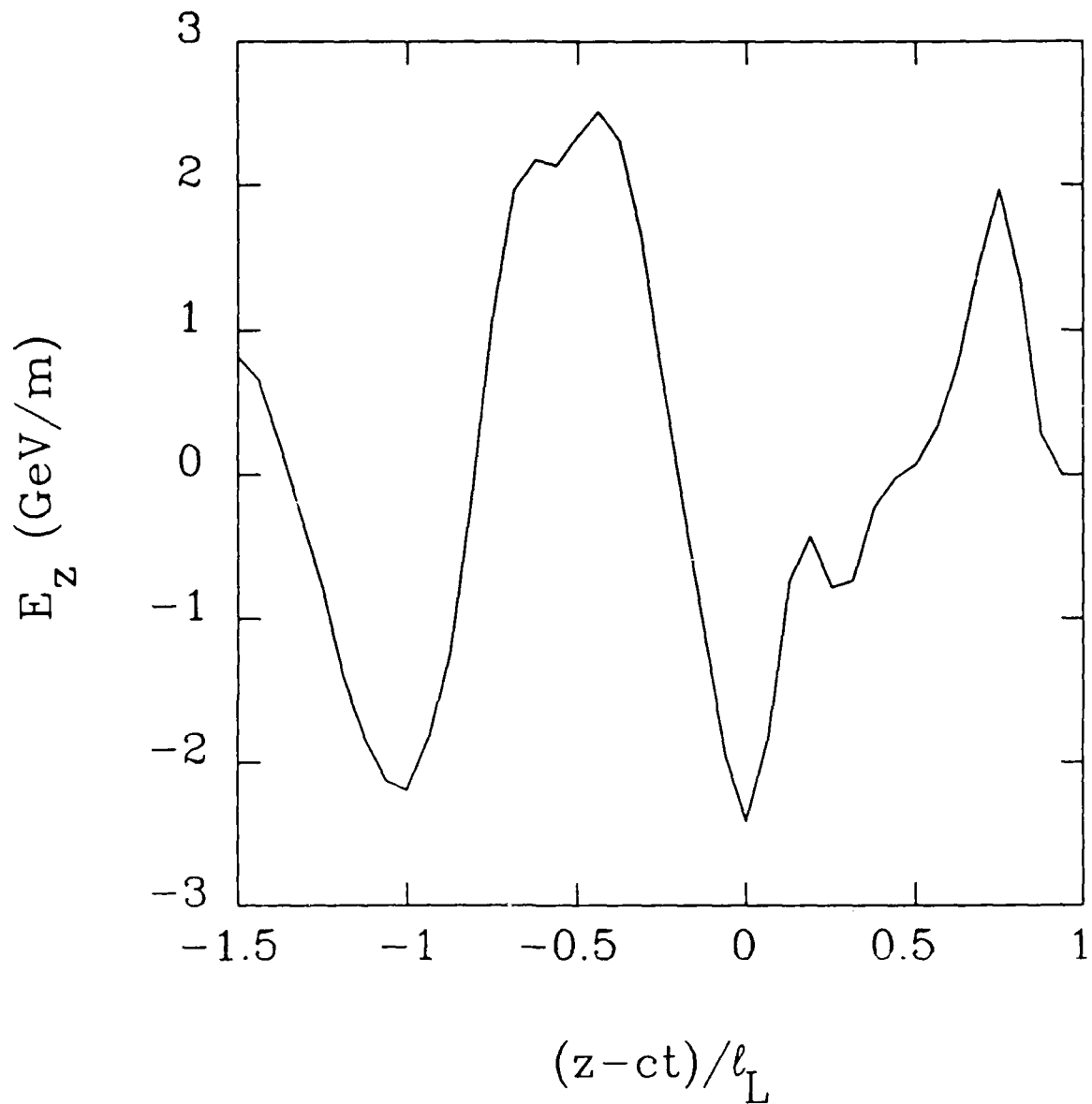


Fig. 3 The axial wakefield obtained from the particle code FRIEZR for the same parameters as in Fig. 2. The laser pulse is modeled by a fixed ponderomotive force which extends over the region  $0 \leq (z-ct)/\ell_L \leq 1$ .

DISTRIBUTION LIST\*

Naval Research Laboratory  
4555 Overlook Avenue, S.W.  
Washington, DC 20375-5000

Attn: Code 1000 - CAPT W. G. Clautice  
1001 - Dr. T. Coffey  
1005 - Head, Office of Management & Admin.  
2000 - Director of Technical Services  
2604 - NRL Historian  
4603 - Dr. W.W. Zachary  
4700 - Dr. S. Ossakow (26 copies)  
4710 - Dr. C.A. Kapetanakos  
4730 - Dr. R. Elton  
4740 - Dr. W.M. Manheimer  
4740 - Dr. S. Gold  
4790 - Dr. P. Sprangle  
4790 - Dr. C.M. Tang  
4790 - Dr. M. Lampe  
4790 - Dr. Y.Y. Lau  
4790A- W. Brizzi  
6652 - Dr. N. Seeman  
6840 - Dr. S.Y. Ahn  
6840 - Dr. A. Ganguly  
6840 - Dr. R.K. Parker  
6850 - Dr. L.R. Whicker  
6875 - Dr. R. Wagner  
2628 - Documents (22 copies)  
2634 - D. Wilbanks  
1220 - 1 copy  
Cindy Sims (Code 2634) 1 copy

Records 1 copy

\* Every name listed on distribution gets one copy except for those where extra copies are noted.

Dr. R. E. Aamodt  
Science Applications Intl. Corp.  
1515 Walnut Street  
Boulder, CO 80302

Dr. B. Amini  
1763 B. H.  
U. C. L. A.  
Los Angeles, CA 90024

Dr. D. Bach  
Los Alamos National Laboratory  
P. O. Box 1663  
Los Alamos, NM 87545

Dr. D. C. Barnes  
Science Applications Intl. Corp.  
Austin, TX 78746

Dr. L. R. Barnett  
3053 Merrill Eng. Bldg.  
University of Utah  
Salt Lake City, UT 84112

Dr. S. H. Batha  
Lab. for Laser Energetics &  
Dept. of Mech. Eng.  
Univ. of Rochester  
Rochester, NY 14627

Dr. F. Bauer  
Courant Inst. of Math. Sciences  
New York University  
New York, NY 10012

Dr. Peter Baum  
General Research Corp.  
P. O. Box 6770  
Santa Barbara, CA 93160

Prof. George Bekefi  
Rm. 36-213  
M.I.T.  
Cambridge, MA 02139

Dr. Russ Berger  
FL-10  
University of Washington  
Seattle, WA 98185

Dr. O. Betancourt  
Courant Inst. of Math. Sciences  
New York University  
New York, NY 10012

Dr. B. Bezzerides  
MS-E531  
Los Alamos National Laboratory  
P. O. Box 1663  
Los Alamos, NM 87545

Dr. Leroy N. Blumberg  
U.S. Dept. of Energy  
Division of High Energy Physics  
ER-224/Germantown  
Wash., DC 20545

Dr. Howard E. Brandt  
Department of the Army  
Harry Diamond Laboratory  
2800 Powder Mill Road  
Adelphi, MD 20783

Dr. Richard J. Briggs  
Lawrence Livermore National Laboratory  
P. O. Box 808, L-626  
Livermore, CA 91550

Dr. Bob Brooks  
FL-10  
University of Washington  
Seattle, WA 98195

Prof. William Case  
Dept. of Physics  
Grinnell College  
Grinnell, Iowa 50221

Mr. Charles Cason  
Commander, U. S. Army  
Strategic Defense Command  
Attn: CSSD-H-D  
P. O. Box 1500  
Huntsville, AL 34807-3801

Dr. Paul J. Channell  
AT-6, MS-H818  
Los Alamos National Laboratory  
P. O. Box 1663  
Los Alamos, NM 87545

Dr. A. W. Chao  
Stanford Linear Accelerator Center  
Stanford University  
Stanford, CA 94305

Dr. Francis F. Chen  
UCLA, 7731 Boelter Hall  
Electrical Engineering Dept.  
Los Angeles, CA 90024



Dr. K. Wendell Chen  
Center for Accel. Tech.  
University of Texas  
P.O. Box 19363  
Arlington, TX 76019

Dr. Pisin Chen  
SLAC, Bin 26  
P.O. Box 4349  
Stanford, CA 94305

Dr. Marvin Chodorow  
Stanford University  
Dept. of Applied Physics  
Stanford, CA 94305

Major Barr Clare  
USASDC  
P. O. Box 15280  
Arlington, VA 22215-0500

Dr. Christopher Clayton  
UCLA, 1538 Boelter Hall  
Electrical Engineering Dept.  
Los Angeles, CA 90024

Dr. Bruce I. Cohen  
Lawrence Livermore National Laboratory  
P. O. Box 808  
Livermore, CA 94550

Dr. B. Cohn  
L-630  
Lawrence Livermore National Laboratory  
P. O. Box 808  
Livermore, CA 94550

Dr. B. Cole  
Univ. of Wisconsin  
Madison, WI 53706

Dr. Francis T. Cole  
Fermi National Accelerator Laboratory  
Physics Section  
P. O. Box 500  
Batavia, IL 60510

Dr. Richard Cooper  
Los Alamos National Laboratory  
P. O. Box 1663  
Los Alamos, NM 87545

Dr. Ernest D. Courant  
Brookhaven National Laboratory  
Upton, NY 11973

Dr. Paul L. Csonka  
Institute of Theoretical Sciences  
and Department of Physics  
University of Oregon  
Eugene, Oregon 97403

Dr. Chris Darrow  
UCLA  
1-130 Knudsen Hall  
Los Angeles, CA 90024

Dr. J. M. Dawson  
Department of Physics  
University of California, Los Angeles  
Los Angeles, CA 90024

Dr. Adam Drobot  
Science Applications Intl. Corp.  
1710 Goodridge Dr.  
Mail Stop G-8-1  
McLean, VA 22102

Dr. D. F. DuBois, T-DOT  
Los Alamos National Laboratory  
Los Alamos, NM 87545

Dr. J. J. Ewing  
Spectra Technology  
2755 Northup Way  
Bellevue, WA 98004

Dr. Frank S. Felber  
11011 Torreyana Road  
San Diego, CA 92121

Dr. Richard C. Fernow  
Brookhaven National Laboratory  
Upton, NY 11973

Dr. H. Figueroa  
1-130 Knudsen Hall  
U. C. L. A.  
Los Angeles, CA 90024

Dr. Jorge Fontana  
Elec. and Computer Eng. Dept.  
Univ. of Calif. at Santa Barbara  
Santa Barbara, CA 93106

Dr. David Forslund  
Los Alamos National Laboratory  
P. O. Box 1663  
Los Alamos, NM 87545

Dr. P. Garabedian  
Courant Inst. of Math. Sciences  
New York University  
New York, NY 10012

Dr. Walter Gekelman  
UCLA - Dept. of Physics  
1-130 Knudsen Hall  
Los Angeles, CA 90024

Dr. Dennis Gill  
Los Alamos National Laboratory  
P. O. Box 1663  
Los Alamos, NM 87545

Dr. B. B. Godfrey  
Mission Research Corporation  
1720 Randolph Road, SE  
Albuquerque, NM 87106

Dr. P. Goldston  
Los Alamos National Laboratory  
P. O. Box 1663  
Los Alamos, NM 87545

Prof. Louis Hand  
Dept. of Physics  
Cornell University  
Ithaca, NY 14853

Dr. J. Hays  
TRW  
One Space Park  
Redondo Beach, CA 90278

Dr. Wendell Horton  
University of Texas  
Physics Dept., RLM 11.320  
Austin, TX 78712

Dr. J. Y. Hsu  
General Atomic  
San Diego, CA 92138

Dr. H. Huey  
Varian Associates  
B-118  
611 Hansen Way  
Palo Alto, CA 95014

Dr. Robert A. Jameson  
Los Alamos National Laboratory  
AT-Division, MS H811  
P.O. Box 1663  
Los Alamos, NM 87545

Dr. G. L. Johnston  
NW16-232  
M. I. T.  
Cambridge, MA 02139

Dr. Shayne Johnston  
Physics Department  
Jackson State University  
Jackson, MS 39217

Dr. Mike Jones  
MS B259  
Los Alamos National Laboratory  
P. O. Box 1663  
Los Alamos, NM 87545

Dr. C. Joshi  
7620 Boelter Hall  
Electrical Engineering Department  
University of California, Los Angeles  
Los Angeles, CA 90024

Dr. E. L. Kane  
Science Applications Intl. Corp.  
McLean, VA 22102

Dr. Tom Katsouleas  
UCLA, 1-130 Knudsen Hall  
Department of Physics  
Los Angeles, CA 90024

Dr. Rhon Keinigs MS-259  
Los Alamos National Laboratory  
P. O. Box 1663  
Los Alamos, NM 87545

Dr. Kwang-Je Kim  
Lawrence Berkeley Laboratory  
University of California, Berkeley  
Berkeley, CA 94720

Dr. S. H. Kim  
Center for Accelerator Technology  
University of Texas  
P.O. Box 19363  
Arlington, TX 76019

Dr. Joe Kindel  
Los Alamos National Laboratory  
P. O. Box 1663, MS E531  
Los Alamos, NM 87545

Dr. Ed Knapp  
Los Alamos National Laboratory  
P. O. Box 1663  
Los Alamos, NM 87545

Dr. Peter Kneisel  
Cornell University  
F. R. Newman Lab. of Nucl. Studies  
Ithaca, NY 14853

Dr. Norman M. Kroll  
University of California, San Diego  
San Diego, CA 92093

Dr. Michael Lavan  
Commander, U. S. Army  
Strategic Defense Command  
Attn: CSSD-H-D  
P. O. Box 1500  
Huntsville, AL 35807-3801

Dr. Kenneth Lee  
Los Alamos National Laboratory  
P.O. Box 1663, MS E531  
Los Alamos, NM 87545

Dr. Baruch Levush  
Dept. of Physics & Astronomy  
University of Maryland  
College Park, MD 20742

Dr. Chuan S. Liu  
Dept. of Physics & Astronomy  
University of Maryland  
College Park, MD 20742

Dr. N. C. Luhmann, Jr.  
7702 Boelter Hall  
U. C. L. A.  
Los Angeles, CA 90024

Dr. Clare Max  
Institute of Geophysics  
& Planetary Physics  
Lawrence Livermore National Laboratory  
P. O. Box 808  
Livermore, CA 94550

Dr. B. D. McDaniel  
Cornell University  
Ithaca, NY 14853

Dr. Colin McKinstrie  
Los Alamos National Laboratory  
P. O. Box 1663  
Los Alamos, NM 87545

Prof. Kim Molvig  
Plasma Fusion Center  
Room NW16-240  
M.I.T.  
Cambridge, MA 02139

Dr. A. Mondelli  
Science Applications Intl. Corp.  
1710 Goodridge Drive  
McLean, VA 22101

Dr. Warren Mori  
1-130 Knudsen Hall  
U. C. L. A.  
Los Angeles, CA 90024

Dr. P. L. Morton  
Stanford Linear Accelerator Center  
P. O. Box 4349  
Stanford, CA 94305

Dr. John A. Nation  
Laboratory of Plasma Studies  
369 Upson Hall  
Cornell University  
Ithaca, NY 14853

Dr. K. C. Ng  
Courant Inst. of Math. Sciences  
New York University  
New York, NY 10012

Dr. Robert J. Noble  
S.L.A.C., Bin 26  
Stanford University  
P.O. Box 4349  
Stanford, CA 94305

Dr. J. Norem  
Argonne National Laboratory  
Argonne, IL 60439

Dr. Craig L. Olson  
Sandia National Laboratories  
Plasma Theory Division 1141  
P.O. Box 5800  
Albuquerque, NM 87185

Dr. H. Oona  
MS E554  
Los Alamos National Laboratory  
P. O. Box 1663  
Los Alamos, NM 87545

Dr. Robert B. Palmer  
Brookhaven National Laboratory  
Upton, NY 11973

Dr. Richard Pantell  
Stanford University  
308 McCullough Bldg.  
Stanford, CA 94305

Dr. John Pasour  
Mission Research Corporation  
8560 Cinderbed Rd.  
Suite 700  
Newington, VA 22122

Dr. Samuel Penner  
Center for Radiation Research  
National Bureau of Standards  
Gaithersburg, MD 20899

Dr. Claudio Pellegrini  
National Synchrotron Light Source  
Brookhaven National Laboratory  
Upton, NY 11973

Dr. Melvin A. Piestrup  
Adelphi Technology  
13800 Skyline Blvd. No. 2  
Woodside, CA 94062

Dr. Z. Pietrzyk  
FL-10  
University of Washington  
Seattle, WA 98185

Dr. Don Prosnitz  
Lawrence Livermore National Laboratory  
P. O. Box 808  
Livermore, CA 94550

Dr. R. Ratowsky  
Physics Department  
University of California at Berkeley  
Berkeley, CA 94720

Dr. Charles W. Roberson  
Office of Naval Research  
Detachment Arlington  
800 North Quincy St., BCT # 1  
Arlington, VA 22217-5000

Dr. Stephen Rockwood  
Los Alamos National Laboratory  
P. O. Box 1663  
Los Alamos, NM 87545

Dr. Harvey A. Rose, T-DOT  
Los Alamos National Laboratory  
Los Alamos, NM 87545

Dr. James B. Rosenzweig  
Dept. of Physics  
University of Wisconsin  
Madison, WI 53706

Dr. Alessandro G. Ruggiero  
Argonne National Laboratory  
Argonne, IL 60439

Dr. R. D. Ruth  
SLAC, Bin 26  
P. O. Box 4349  
Stanford, CA 94305

Dr. Jack Sandweiss  
Gibbs Physics Laboratory  
Yale University  
260 Whitney Avenue  
P. O. Box 6666  
New Haven, CT 06511

Dr. Al Saxman  
Los Alamos National Laboratory  
P.O. Box 1663, MS E523  
Los Alamos, NM 87545

Prof. John Scharer  
Electrical & Computer Engineering Dept.  
University of Wisconsin  
Madison, WI 53706

Dr. George Schmidt  
Stevens Institute of Technology  
Department of Physics  
Hoboken, NJ 07030

Dr. N. C. Schoen  
TRW  
One Space Park  
Redondo Beach, CA 90278

Dr. Frank Selph  
U. S. Department of Energy  
Division of High Energy Physics, ER-224  
Washington, DC 20545

Dr. Andrew M. Sessler  
Lawrence Berkeley Laboratory  
University of California, Berkeley  
Berkeley, CA 94720

Dr. Richard L. Sheffield  
Los Alamos National Laboratory  
P.O. Box 1663, MS H825  
Los Alamos, NM 87545

Dr. John Siambis  
Lockheed Palo Alto Research Laboratory  
3251 Hanover Street  
Palo Alto, CA 94304

Dr. Robert Siemann  
Dept. of Physics  
Cornell University  
Ithaca, NY 14853

Dr. J. D. Simpson  
Argonne National Laboratory  
Argonne, IL 60439

Dr. Charles K. Sinclair  
Stanford University  
P. O. Box 4349  
Stanford, CA 94305

Dr. Sidney Singer  
MS-E530  
Los Alamos National Laboratory  
P.O. Box 1663  
Los Alamos, NM 87545

Dr. R. Siusher  
AT&T Bell Laboratories  
Murray Hill, NJ 07974

Dr. Jack Slater  
Mathematical Sciences, NW  
2755 Northup Way  
Bellevue, WA 98009

Dr. Todd Smith  
Hansen Laboratory  
Stanford University  
Stanford, CA 94305

Dr. Richard Spitzer  
Stanford Linear Accelerator Center  
P. O. Box 4347  
Stanford, CA 94305

Mr. L. J. Su  
UCLA  
1-120 Knudsen Hall  
Los Angeles, CA 90024

Prof. Ravi Sudan  
Electrical Engineering Department  
Cornell University  
Ithaca, NY 14853

Dr. Don J. Sullivan  
Mission Research Corporation  
1720 Randolph Road, SE  
Albuquerque, NM 87106

Dr. David F. Sutter  
U. S. Department of Energy  
Division of High Energy Physics, ER-224  
Washington, DC 20545

Dr. T. Tajima  
Department of Physics  
and Institute for Fusion Studies  
University of Texas  
Austin, TX 78712

Dr. Lee Teng, Chairman  
Fermilab  
P.O. Box 500  
Batavia, IL 60510

Dr. H. S. Uhm  
Naval Surface Warfare Center  
White Oak Laboratory  
Silver Spring, MD 20903-5000

U. S. Naval Academy (2 copies)  
Director of Research  
Annapolis, MD 21402

Dr. William A. Wallenmeyer  
U. S. Dept. of Energy  
High Energy Physics Div., ER-22  
Washington, DC 20545

Dr. John E. Walsh  
Department of Physics  
Dartmouth College  
Hanover, NH 03755

Dr. Tom Wangler  
Los Alamos National Laboratory  
P. O. Box 1663  
Los Alamos, NM 87545

Dr. S. Wilke  
Physics Dept.  
1-120 Knudsen Hall  
UCLA  
Los Angeles, CA 90024

Dr. Perry B. Wilson  
Stanford Linear Accelerator Center  
Stanford University  
P.O. Box 4349  
Stanford, CA 94305

Dr. W. Woo  
Applied Science Department  
University of California at Davis  
Davis, CA 95616

Dr. Jonathan Wurtele  
M.I.T.  
NW 16-234  
Plasma Fusion Center  
Cambridge, MA 02139

Dr. Yi-Ton Yan  
Los Alamos National Laboratory  
MS-K764  
Los Alamos, NM 87545

Dr. M. Yates  
Los Alamos National Laboratory  
P. O. Box 1663  
Los Alamos, NM 87545

Dr. Ken Yoshioka  
Laboratory for Plasma and Fusion  
University of Maryland  
College Park, MD 20742

Dr. R. W. Ziolkowski, L-156  
Lawrence Livermore National Laboratory  
P. O. Box 808  
Livermore, CA 94550

END  
DATE  
FILMED  
12-88  
DTIC